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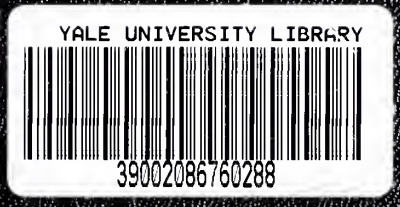
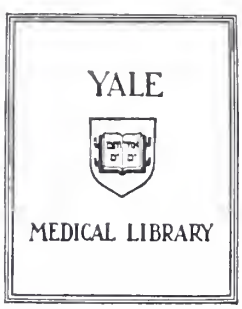


CANINE MODELING OF THE HUMAN CERVICAL SPINE

Edward David Wang

YALE UNIVERSITY

1990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Canine Modeling Of The Human Cervical Spine

A Thesis Submitted to the Yale University
School of Medicine in Partial Fulfillment
of the Requirements for the Degree of Doctor of Medicine

By

Edward David Wang

1990

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To my parents and Joy

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ABSTRACT

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1990

The overall purpose of this investigation was to determine whether or not the canine cervical spine was an accurate model for the human cervical spine with respect to motion and therefore, stability. This was divided into three goals: 1) to illustrate the three-dimensional motion of the intact canine cervical spine, 2) to illustrate the three-dimensional motion of the injured canine cervical spine, 3) to compare the canine results to analogous human data published by previous authors.

Stereophotogrammetry techniques were used to measure the in vitro range of motion for five specimens (C2-C7) during flexion-extension, lateral bending, and axial rotation in the intact situation as well as following each of three increasingly severe injuries at C4-5 -- laminectomy, bilateral capsulectomy, and bilateral facetectomy.

Regarding the intact cervical spine, the canine had a different distribution of motion with respect to vertebral level from that of the human. The other main difference was that the canine was much more flexible than the human. Regarding the injured situation, both spines behaved similarly. Injury at a specific site affected the motion of the entire spine in both the canine and human. The other similarity between the two was a post-facetectomy fall in range of motion at the injury site.

From these observations, it was concluded that although for the intact, the two behaved somewhat differently, for the injured case, the canine exhibited motion and hence, stability behavior accurately modeling that of the human.

ACKNOWLEDGEMENTS

This investigation was performed at the Biomechanics Laboratory, Department of Orthopaedics and Rehabilitation, Yale University School of Medicine.

Much credit for this work must be given to Dr. Manohar M. Panjabi for providing the author with the opportunity and the resources to pursue his interest in biomechanics. The research experience along with the overall experience of being a Yale medical student has been valuable preparation for the self-educational process inherent to ultimately becoming a successful physician.

Acknowledgements are to be given to Dr. J.J. "Trey" Crisco for his technical support as well as to Mr. Thomas R. Oxland for his valuable assistance.

New Haven, Connecticut
February 1990
E.D. Wang

INTRODUCTION

The spine is a unique structure. It must serve two very different functions (White et al. 1974). It must not only provide a tough durable shell protecting the spinal cord from injury, but it must also provide the flexibility needed for the bending and twisting of everyday life. As an example, an automobile top has yet to be invented, which can combine the strength and protection of the hardtop's steel with the flexibility of the convertible's canvas.

As a review of the literature will illustrate more specifically, the work by Lysell (1969) highlighted the study of the three-dimensional motion of the intact cervical spine. Working together, Panjabi et al. (1975) and White et al. (1975) studied the injured cervical spine. Using motion behavior as a measure of stability, these two investigators were able to establish certain criteria for the determination of clinical instability. Goel et al. (1984) also investigated the three-dimensional motion of the injured cervical spine.

Clearly, the next step, following the above studies, all using human autopsy specimens, was to investigate the injured cervical spine in living subjects. These subjects, in contrast to the autopsy specimens, could respond actively to injury. Panjabi et al. (1988) took this step when he studied the effects of injury and healing on live canines. A possible caveat of this work, however, and of others which use the canine to model the human, is that no existing study compares the behavior of the canine and human cervical spines with respect to motion and hence, stability -- the two being inversely related. Therefore, an important question arises: Is the canine indeed an accurate model for the human with respect to three-dimensional motion and stability?

This investigation seeks to answer that question. The hypothesis is that enough similarity exists between the two to enable the canine to continue as a successful in vitro model. The present investigation hopes to support the hypothesis and accomplish three goals:

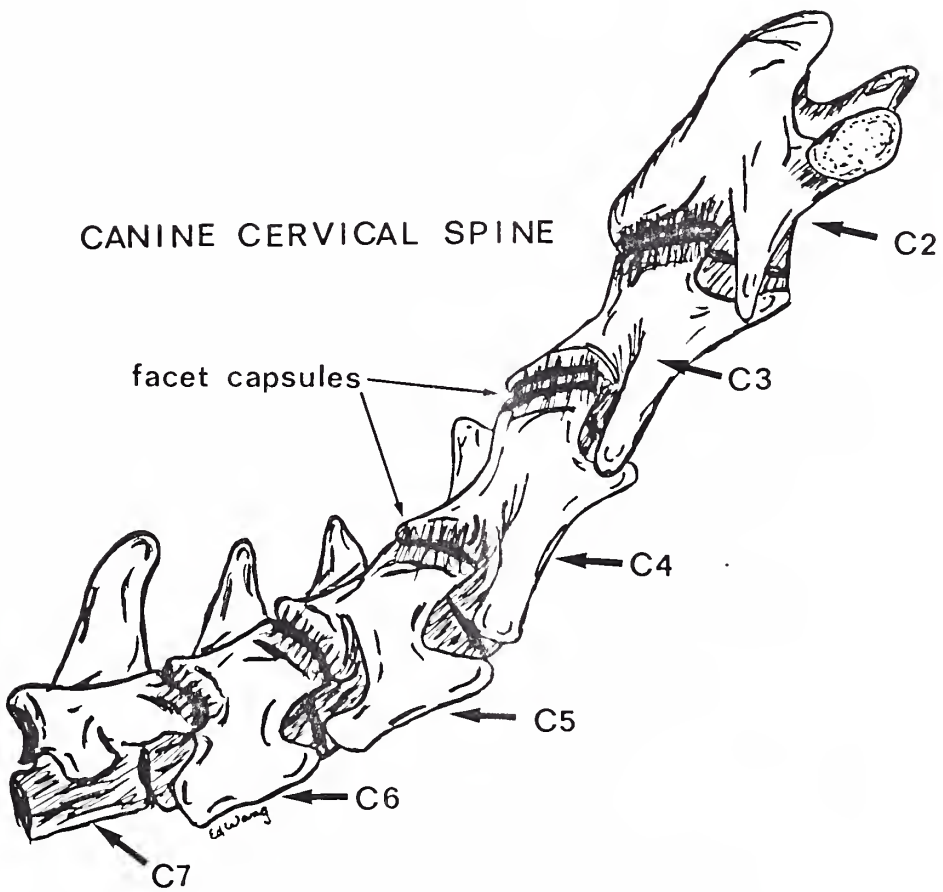
I. To illustrate the three-dimensional motion of the intact canine cervical spine,

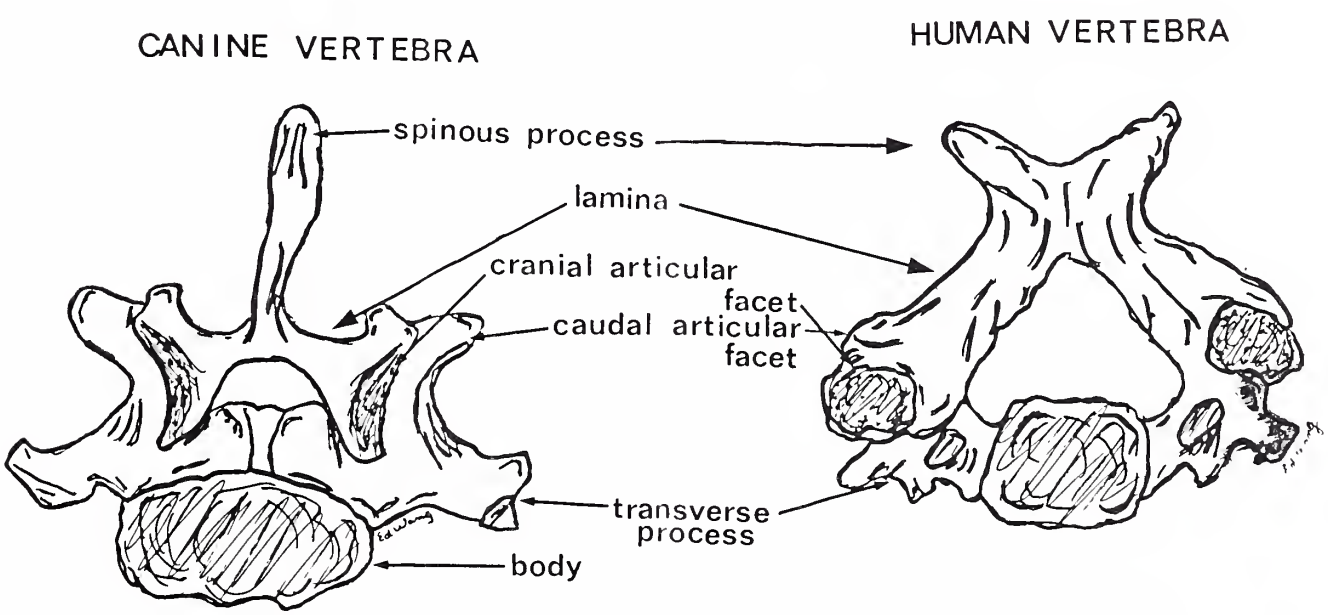
II. To illustrate the three-dimensional motion of the injured canine cervical spine,

III. To compare the results of the present canine studies to analogous data for the human, which have been published by previous authors.

ANATOMY REFERENCE

The drawings below are meant as an orientation to referenced anatomy.





TERMS AND DEFINITIONS

The following terms and definitions are listed here to illustrate their usage in the context of this investigation.

Three-dimensional motion -- Although translation is part of three-dimensional motion, the present results are restricted to rotation in the frontal, sagittal, or horizontal plane.

Stability -- This is defined as being inversely related to the range of motion such that increased range of motion correlates to decreased stability as well the converse.

Clinical stability -- This means the "the ability of the spine under physiological loads to maintain relationships between the vertebrae in such a way that there is neither damage nor subsequent irritation to the spinal cord or nerve roots and, in addition, there is no development of incapacitating deformity or pain due to structural changes," as stated by Panjabi and White (1980).

Range of motion (ROM) -- This refers to the total range of rotation of a vertebra in either the frontal, sagittal, or transverse plane as measured with respect to the immediately subjacent vertebra.

Flexion-extension ROM-- This equals the sum total motion in the sagittal plane, directed in the anterior and posterior directions.

Lateral bending ROM-- This equals the sum total motion in the frontal plane to both sides, right and left.

Axial rotation ROM-- This equals the sum total motion in the transverse plane to both sides, right and left..

REVIEW OF THE LITERATURE

The following review of the literature focuses on the more relevant investigations which help to manifest the importance and place of the present study. This is not intended to be an exhaustive historical account of all the work done in the area of spine research. For such a review, one may consult Elward (1939), Andersson and Ekström (1940), and Lysell (1969).

Lysell (1969) presented a definitive study for the motion of the intact human cervical spine. His investigation focused on the angular range of motion of each vertebra during flexion-extension, lateral bending, and axial rotation following the application of shear loads. His range of motion measurements were recorded with respect to the vertebra directly subjacent. The methods he used involved taking two radiographs of the specimens at fixed angles to one another. The specimens included vertebrae C2 through T1. Steel balls embedded in each vertebra created reference points from which geometric calculations could be done to reproduce the three-dimensional range of motion. These measurements were within the limits reported by earlier authors also studying the cervical spine. A detailed compilation of the actual values recorded by these individuals is available in Lysell (1969), an investigation which helped to establish the foundation for further work concerning the motion of the human cervical spine. The present investigation hopes to provide a similar foundation regarding the use of the canine model.

Advancing from work with the intact cervical spine, Panjabi et al. (1975) and White et al. (1975) provided studies of motion for the injured cervical spine. In these two studies, the contribution of various anatomic structures to the stability of the

cervical spine was analyzed. This was done by the sequential transection of these structures. By applying shear loads and measuring the range of motion of the specimens after each of these transections, the stability of the spine as a function of injury was quantified.

In their studies, the specimens were divided into two groups. One group underwent sequential injury in the anterior to posterior direction; the other group in the reverse direction. By measuring the range of motion after each injury, they found that little change occurred in stability until a key number of structures were destroyed. When this turning point was reached, an abrupt and large increase in range of motion was seen, signifying failure. Qualitatively, when the spine failed, it either broke completely apart or bent over at an angle exceeding 90°. The minimal number of structures needed for stability was found to be "all the anterior structures 'plus one' additional structure" or the converse, "all the posterior structures 'plus one' additional structure." The anterior structures were defined as including the posterior longitudinal ligament and all structures anterior to it. The posterior structures were the remaining ones. By measuring the motion behavior following injury, Panjabi et al. (1975) and White et al. (1975) not only established anatomic criteria for stability, but also critical horizontal displacement and rotation values. A potentially unstable cervical spine was one which appeared on lateral x-ray to possess a horizontal displacement in excess of 3.5mm or an angulation of more than 11° for any vertebra with respect to the one immediately subjacent to it .

In contrast to Panjabi et al. (1975) and White et al. (1975), whose investigations concentrated on flexion-extension at the injury site, Goel et al. (1984) studied the three-dimensional motion (flexion-extension, lateral bending, and axial rotation) at the injury site as well as at the uninjured site one level above. Goel et al. (1984) sequentially transected the posterior elements of the cervical spine at C5-6,

applying pure moments to test the range of motion after each injury. This study did not proceed to failure.

The major findings of Goel et al. (1984) at the injury site substantiated those reported by Panjabi et al. (1975) and White et al. (1975). Chief among these observations was that range of motion changed little until after capsular ligament injury. Additional data reported by Goel et al. (1984), concerning the range of motion of the uninjured site (C4-5), showed that the range of motion here, also increased most noticeably after the capsular ligament was injured at C5-6. Therefore, it appeared that at both the injured and the uninjured sites capsular ligament damage had similar effects. Goel et al. (1984) attributed these effects to loosening of uninjured structures and to ill-defined passive compensation by uninjured vertebrae, resulting from damage to the spine.

Concerning the study of motion in the human cervical spine, each of the studies cited thus far suffer from limitations inherent to using human cadaver material. Any active physiological response which might have occurred as a result of injury could not be studied. Therein lies the importance of Panjabi et al. (1988), which investigated the natural history of healing in the injured canine. This study involved the division of mongrel canines into one of four test groups, each group undergoing a different type of injury at C4-5: 1) sham, 2) supraspinous and interspinous ligament transection, 3) laminectomy, and 4) bilateral facetectomy of the inferior articular facets. The dogs were allowed to heal without stabilization devices for a period of 24 weeks and pure moments were used to test their range of motions periodically.

The major findings at the injury site in this study included the observation of an immediate post-operative decrease in range of motion, attributed to muscle spasm. This was followed by an eventual return to the values of the controls. The conclusion was that the healing process was responsible for the eventual stabilization of the injured canines.

While the findings of Panjabi et al. (1988) are important, the author himself addresses the caveat of using the canine to model the human cervical spine: "...the present findings should be extrapolated to the human condition with great caution."

How much caution? To this question and others, this investigation will hopefully provide some valuable answers and allow future investigators to evaluate the results of canine modelling more critically.

MATERIALS AND METHODS

Materials

Five mongrel canines were sacrificed. The cervical spines (C2-C7) with paraspinous musculature intact were removed from the animals, placed into doubled plastic bags, and stored frozen (-20° C).

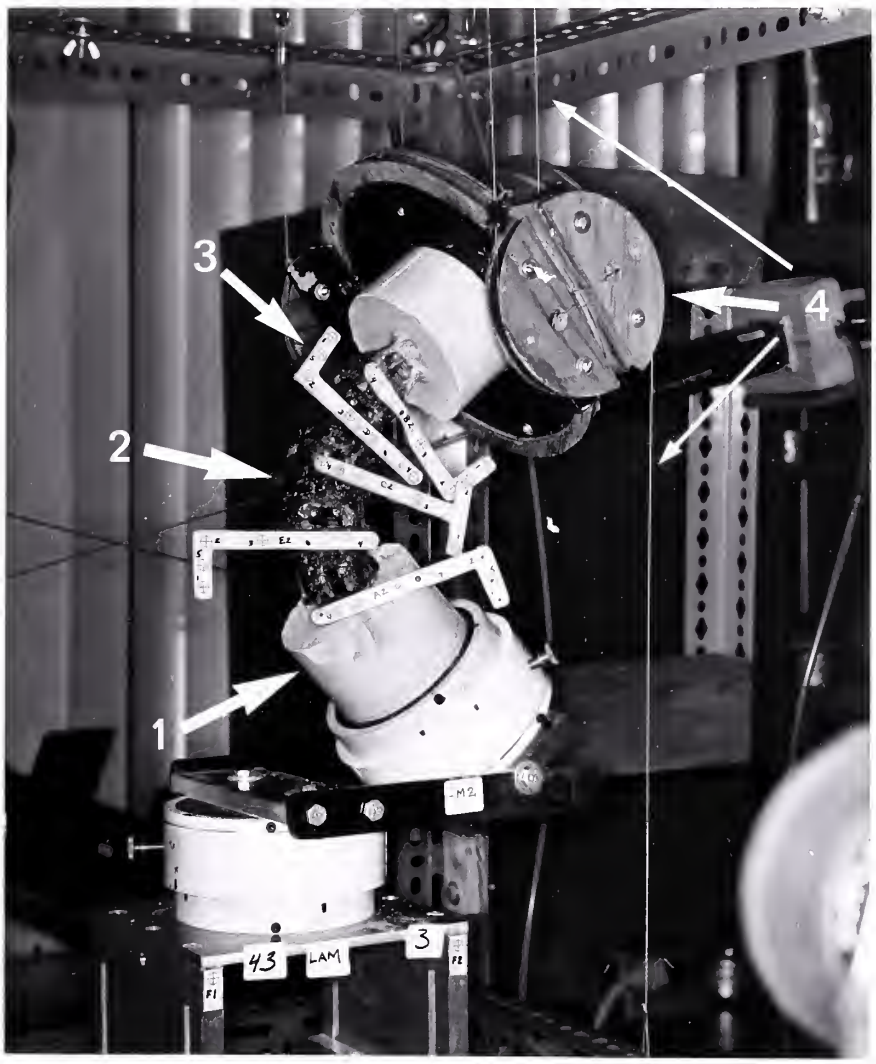
Specimen Preparation

Prior to biomechanical testing, the spines were thawed and dissected of all muscle tissue, leaving the bony structures and associated ligaments intact. During dissection and subsequent handling, care was taken to prevent dessication. The end vertebrae, C2 and C7, were cast in dental cement (Die-Keen, Columbus Dental, St. Louis, Mo). This allowed fixation of the specimen to the testing apparatus. Vertebral markers, labeled with three non-colinear points and 0.8 mm diameter steel balls, were fixed to each vertebra. These markers allowed the angular displacements of the vertebrae to be measured using stereophotogrammetry as described below. One specimen is pictured in the following photograph.

Testing Procedure

Pure moments were applied to the intact specimens in a stepwise manner quasi-statically. These moments induced one of the following types of motions: flexion-

extension, lateral bending, or axial rotation. A specifically designed flexibility apparatus was designed to enable the application of pure moments despite large intervertebral displacements. This apparatus, consisting of a system of cables, pneumatic actuators, and pulleys is pictured in the following photograph with one of the test specimens.



Photograph of the Testing Apparatus. The testing apparatus is pictured above. (1) points to the canine cervical spine. (2) points to the dental cement used to mount the two ends of the spine onto the testing apparatus. (3) points to the vertebral markers used in the photographs to visually quantify the three-dimensional motion of each vertebra. (4) points to the system of pulleys and cables used to apply the pure moments. The two cameras used to record the photographic data are not shown.

For each moment applied, angulations for each type of motion were recorded. The loading cycle for the applied moments was the following: 0.0, 0.5, 1.0, 1.5 Newton-meters. This cycle was repeated three times with motion being recorded on the third cycle. Maintaining the moment application for 30 seconds at each load step in the cycle minimized any short-term visco-elastic effects.

The angular displacements during each type of motion were recorded photographically using two 35 mm cameras located at fixed locations to one another. The weight of the vertebral bodies was not counterbalanced, resulting in a small compressive pre-load which simulated the physiologic weight of the skull.

After completion of the above procedure, the specimens underwent a sequence of injuries. After each injury, the spines were tested in a manner identical to that of the intact spines. A description of the injuries is as follows:

1) Laminectomy at the C4 vertebra,
2) Injury 1 and bilateral capsular ligament transection at the C4-5 facets,
3) Injury 2 and bilateral removal of the inferior facets of C4.

Data Analysis

After completion of the testing, the photographs were developed, mounted, and digitized using a appropriate computer program on an IBM compatible computer, connected to an Altek digitizer (Altek Corporation, Silver Spring, Md), (63 x 63 cm^2, accuracy $\pm$ 0.075 mm). Using a stereo-reconstruction program -- Direct Linear Transformation, originally reported by Marzan and Karara (1975) -- the three-dimensional coordinates of the vertebral markers were determined. Another program was used to determine the angular motions of each vertebra relative to its subjacent equivalent. The approximate accuracy of the measurements was $\pm$ 0.8°. Note that the

ranges of motion for lateral bending and axial rotation were the sum total of the angular rotations to both sides, right and left.

For each type of motion, the mean range of motion value and standard deviation were computed. Tests of statistical significance were performed using a single factor Analysis of Variance and post-hoc Scheffé 's F-test at a 95% confidence level.

RESULTS

The mean three-dimensional ranges of motion (degrees) for each vertebra of the intact canine cervical spine and the standard deviations are presented in table 1. The vertebral levels are represented by the rows. The three types of motion -- flexion-extension, lateral bending, and axial rotation -- are represented by the columns. The data in table 1 are graphed in figures 1A, 1B, and 1C. In each of these graphs, the horizontal axes correspond to the vertebral level, while the vertical axes correspond to the range of motion. The three graphs -- 1A, 1B, and 1C -- match the three types of motion -- flexion-extension, lateral bending, and axial rotation -- respectively.

	Flexion-extension	Lateral Bending	Axial Rotation
C2-3	24.6 (6.05)	41.4 (30.96)	9.9 (3.00)
C3-4	30.0 (4.48)	30.4 (6.99)	11.6 (1.95)
C4-5	26.6 (6.43)	42.8 (13.62)	13.6 (3.68)
C5-6	28.7 (1.65)	63.0 (25.36)	10.7 (1.42)

TABLE 1. Intact Canine: Three-Dimensional Range of Motion of the Cervical Spine. Mean range of motion in degrees with standard deviations are presented above for the intact canine cervical spine. The three columns -- flexion-extension, lateral bending, and axial rotation-- represent the types of motion studied. The four rows -- C2-3, C3-4, C4-5, C5-6 -- represent the vertebral levels. The lateral bending and axial rotation measurements included the sum total ranges of motion to both sides, left and right. Please see the text for further details.

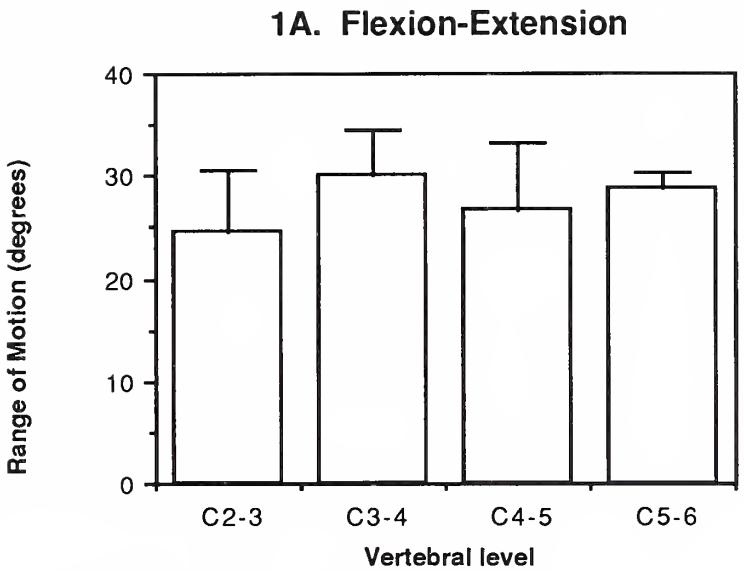


FIGURE 1A. Flexion-Extension of the Intact Canine. The data presented earlier in table 1 for flexion-extension of the intact canine cervical spine is represented graphically. The horizontal axis corresponds to the vertebral level and the vertical axis represents the range of motion in degrees. The error bars represent the standard deviations. Please see the text for a discussion of the graph.

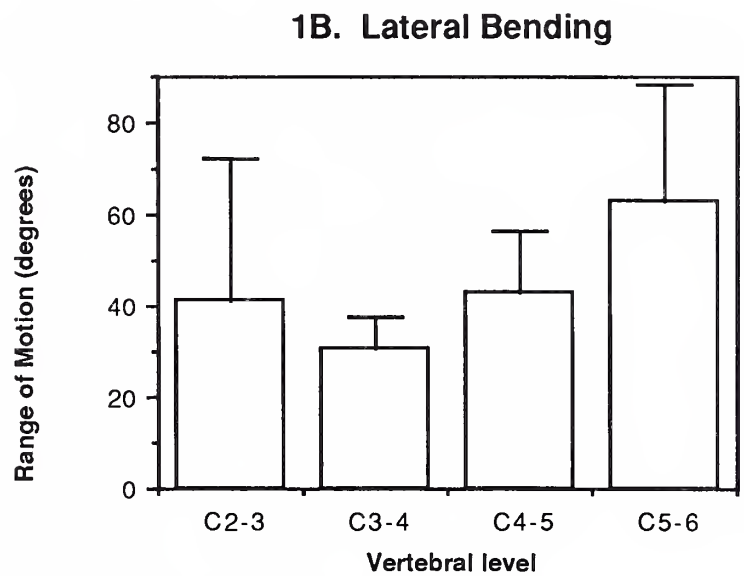


FIGURE 1B. Lateral Bending of the Intact Canine. The data presented in table 1 for lateral bending (sum total to both sides) is represented graphically. The horizontal axis corresponds to the vertebral level and the vertical axis represents the range of motion in degrees. The error bars represent the standard deviations. Please see the text for a discussion of the graph.

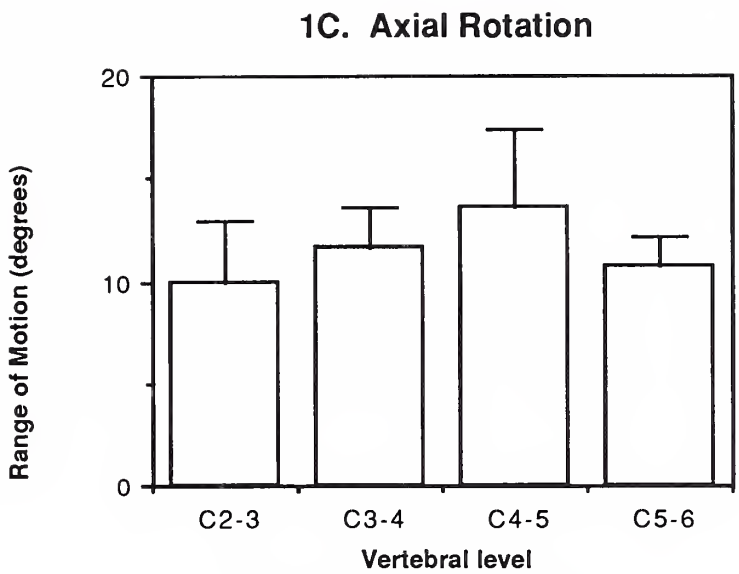


FIGURE 1C. Axial Rotation of the Intact Canine. The data presented in table 1 for axial rotation (sum total to both sides) is represented graphically. The horizontal axis corresponds to the vertebral level and the vertical axis represents the range of motion. The error bars represent the standard deviations. Please see the text for a discussion of the graph.

The data for the injured canine cervical spine are presented in table 2, which has been divided into three parts according to the type of motion involved. The rows correspond to the vertebral level, while the columns correspond to the injury group. These injuries took place only at C4-5, as discussed in the materials and methods section. The data in table 2 are graphed in figures 2A, 2B, and 2C. In these graphs, for each vertebral level on the horizontal axes, the differently shaded bars correspond to the different injury groups as depicted in the key. The intact group has been included for comparison. The vertical axes are the range of motion values as a percentage of the respective intact values. Naturally, the intact bars measure 100 % on the vertical axis.

2A. FLEXION-EXTENSION

	Intact	Laminectomy	Capsulectomy	Facetectomy
C2-3	24.6 (6.05)	27.1 (6.53)	30.2 (6.91)	28.8 (6.82)
C3-4	30.0 (4.48)	33.7 (6.97)	37.6 (7.38)	38.2 (6.75)
C4-5	**26.6 (6.43)**	**34.5 (8.32)**	**56.4 (4.62)**	**45.4 (4.98)**
C5-6	28.7 (1.65)	29.1 (8.64)	38.5 (10.9)	32.9 (6.87)

2B. LATERAL BENDING

	Intact	Laminectomy	Capsulectomy	Facetectomy
C2-3	41.4 (30.9)	28.6 (2.70)	32.1 (6.98)	31.6 (6.39)
C3-4	30.4 (6.99)	33.2 (2.43)	35.9 (4.71)	35.7 (5.18)
C4-5	**42.8 (13.6)**	**38.6 (4.36)**	**51.6 (8.12)**	**45.7 (8.06)**
C5-6	63.0 (25.3)	70.4 (19.7)	52.8 (8.99)	57.0 (23.7)

2C. AXIAL ROTATION

	Intact	Laminectomy	Capsulectomy	Facetectomy
C2-3	9.9 (3.00)	9.6 (1.47)	11.1 (3.73)	16.2 (7.84)
C3-4	11.6 (1.95)	11.3 (5.08)	16.9 (2.22)	14.8 (4.42)
C4-5	**13.6 (3.68)**	**9.8 (6.20)**	**19.8 (3.87)**	**16.5 (7.17)**
C5-6	10.7 (1.42)	8.6 (2.87)	13.3 (8.60)	20.8 (24.5)

TABLE 2. Injured Canine: Three-Dimensional Range of Motion of the Cervical Spine. Mean range of motion in degrees with standard deviations are presented above for the injured canine. Table A presents the data for flexion-extension. Tables B and C present the same for lateral bending and axial rotation (sum totals to both sides), respectively. The columns represent the intact spine plus the three injuries --laminectomy, capsulectomy, and facetectomy. The rows represent the vertebral levels. Please note that the injuries were only at C4-5. Please see the text for further details.

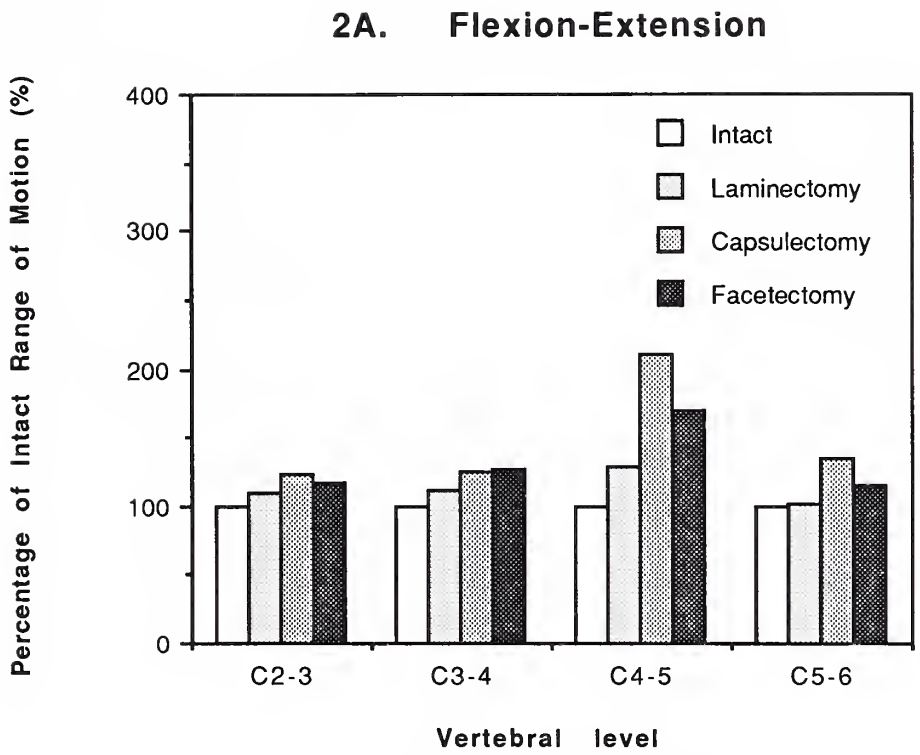


FIGURE 2A. Flexion-Extension of the Injured Canine. The data from table 2 for flexion-extension of the injured canine are represented graphically. The horizontal axis represents the vertebral level. The vertical axis is the range of motion as a percentage of the intact. At each vertebral level, the range of motion for the intact spine, measuring 100%, as well as that of each injury -- laminectomy, capsulectomy, and facetectomy -- is represented by the differently shaded bars.

Note that the injuries took place only at C4-5 and that subsequent measurements at the uninjured sites were taken after each of these injuries. Please refer to the text for further details.

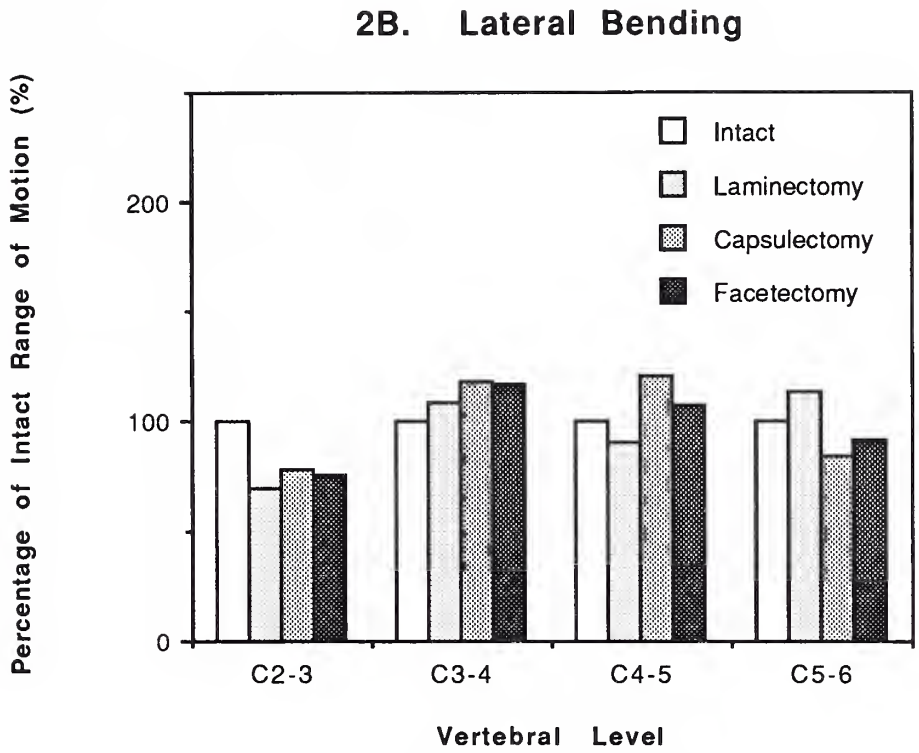


FIGURE 2B. Lateral Bending of the Injured Canine. The data from table 2 for lateral bending (sum total to both sides) of the injured canine are represented graphically. The horizontal axis represents the vertebral level. The vertical axis is the range of motion as a percentage of the intact. At each vertebral level, the range of motion for the intact spine, measuring 100%, as well as that of each injury -- laminectomy, capsulectomy, and facetectomy -- is represented by the differently shaded bars. Please refer to the text for further details.

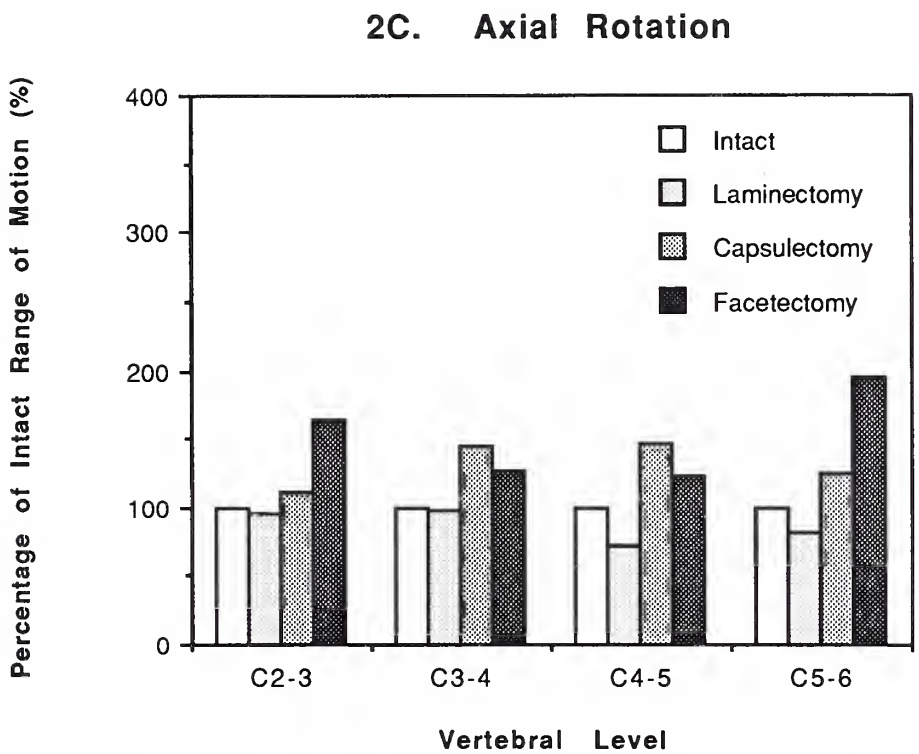


FIGURE 2C. Axial Rotation of the Injured Canine. The data from table 2 for axial rotation (sum total to both sides) of the injured canine are represented graphically. The horizontal axis represents the vertebral level. The vertical axis is the range of motion as a percentage of the intact. At each vertebral level, the range of motion for the intact spine, measuring 100%, as well as that of each injury -- laminectomy, capsulectomy, and facetectomy -- is represented by the differently shaded bars. Please refer to the text for further details.

Intact Canine: Flexion-Extension, Lateral Bending, and Axial Rotation

Looking at the motion of the intact canine cervical spine in figure 1A, the range of motion for flexion-extension varied with no apparent pattern. In contrast, the lateral bending in figure 1B dropped from C2-3 to C3-4, then followed a trend of steady increase from C3-4 through C5-6. Similarily, figure 1C showed that axial rotation gradually increased from C2-3 through C4-5, followed by a drop at C5-6. Despite these patterns, however, statistical analysis revealed that no significant differences existed for any of the data of figures 1A, 1B, and 1C.

Comparisons between the different types of motion for the intact canine as represented in figure 1 reveal that in general the canine cervical spine tends to have the greatest range of motion in lateral bending (34.0°-63.0°), followed in order by flexion-extension (24.6°-30.0°), and axial rotation (10.0°-13.6°).

Injured Canine: Flexion-Extension

With regards to flexion-extension in the injured canine cervical spine, as represented by figure 2A, all of the vertebral levels (C2-C7) showed an increase in range of motion over the intact after each injury. The most dramatic increases occurred at the injury site, C4-5. These were the only ones found to be statistically significant .

Another interesting finding could be seen by concentrating on C4-5 after each sequential injury. The range of motion appeared to increase from laminectomy to capsulectomy, but decreased following facetectomy. This pattern could also be seen at levels C2-3 and C5-6. An alternative pattern showed the same increase from laminectomy to capsulectomy, but then it showed a further increase following facetectomy. This could be seen at level C3-4.

Injured Canine: Lateral Bending

Figure 2B, showing the lateral bending behavior, painted a different picture from that of flexion-extension. At C2-3, for example, there was a decrease and not an increase in range of motion over the intact for each injury. On the other hand, C3-4 showed an increase over the intact for all injuries. C4-5 and C5-6 did not show either of these two tendencies, instead varying in their responses.

Despite these differences from flexion-extension, lateral bending at C2-3, C3-4, and C4-5 showed the pattern of increasing from laminectomy to capsulectomy, then decreasing following facetectomy. C5-6 was the only exception to this rule.

Injured Canine: Axial Rotation

The axial rotation as pictured in figure 2C behaved similarily to lateral bending. Rather than the consistent increase in range of motion of the injury groups over the intact as seen in flexion-extension, a more variable response occurs.

The two patterns concerned with the injury-to-injury change, as described for flexion-extension, applied to axial rotation as well. C3-4 and C4-5 illustrated the pattern of an increase in range of motion from laminectomy to capsulectomy, then a decrease following facetectomy. C2-3 and C5-6, on the other hand, illustrated the alternative pattern, an increase from laminectomy to capsulectomy, then a further increase following facetectomy.

DISCUSSION

The following discussion section, separated into three parts, follows the outline set forth in the introduction section. The first part discusses the three-dimensional motion of the intact canine cervical spine; the second discusses the three-dimensional motion of the injured canine cervical spine; and the third discusses a comparison of these canine investigations to analogous data for the human, as published by other authors.

Three-dimensional Motion of the Intact Canine Cervical Spine

Two interesting observations manifested themselves in the range of motion for the intact canine spine. The first observation pertained to the relative distribution of motion with respect to vertebral level. For example, in figure 1B, illustrating lateral bending, at the two ends of the cervical spine, C2-3 and C5-6, there tended to be more range of motion than in comparison to the middle of the spine, C3-4. The opposite distribution appeared to occur for axial rotation, pictured in figure 1C. For flexion-extension, as pictured in figure 1A, a variable distribution seemed to exist, with no evident trends. Thus, depending on the applied moment, the range of motion for the intact canine seemed to possess a characteristic distribution with respect to vertebral level.

The second observation pertained to the relative magnitude, when comparing the different types of motion. For instance, the lateral bending values were in general the highest (30°-60°), followed in order by flexion-extension (20°-30°) and axial

rotation (~10°). Overall, it seemed that the intact canine spine tended to rely more heavily on lateral bending, less on flexion-extension, and least on axial rotation.

Three-dimensional Motion of the Injured Canine Cervical Spine

As stated earlier in the literature review, Goel et al. (1984) showed that following injury, the human cervical spine not only increased its range of motion at the injured site, but also at the adjacent site. Explanations for this behavior, as discussed in this work, included loosening of the intact structures of the adjacent vertebra. In other words, the foundations of these intact structures appeared to be compromised by nearby damage. Another possible explanation suggested that the altered range of motion seen at the uninjured site was due to passive compensation, which resulted from an attempt by the cervical spine to redistribute altered motion at the injured site to other vertebral levels. Thus, it seemed that a well-defined injury at one vertebra affected the stability of the entire vertebral column. Whether this was due to loosening, passive compensation, or more likely a combination, the human cervical spine appeared to function as one construct of closely interacting components, and not simply as a loose link of independent units.

The canine appeared to behave similarily to the human, following injury. In figures 2A, 2B, and 2C, injury at C4-5 resulted in a change in the motion at the other vertebrae. As seen in figure 1A, flexion-extension at all of the uninjured levels (C2-3, C3-4, and C5-6) increased over the intact's range of motion. This could have been due to a combination of loosening and passive compensation as discussed in the human. Lateral bending and axial rotation showed more variability. Some levels showed an increase over the intact; others, a decrease; and the remainder, a combination. Examples of these behaviors were C3-4 in figure 2B, C2-3 in figure 2B, and C5-6 in figure 2C, respectively.

Another interesting observation was illustrated by concentrating on an individual vertebral level and its individual response to injury in the cervical spine. This response appeared to follow one of two patterns. Level C4-5 in figure 2C represented an example of the first pattern. Here, the range of motion increased from laminectomy to capsulectomy, and then it decreased following facetectomy. This same observation applied to C3-4 in the same figure. In contrast, levels C2-3 and C5-6 showed the other pattern, namely, an increase in range of motion from laminectomy to capsulectomy, and then a further increase following facetectomy. Overall, every vertebra in figures 2A, 2B, and 2C showed one of these two patterns of response to injury in the canine cervical spine, the only exception being C5-6 of figure 2B.

Worth particular attention was the injury site, C4-5. This always showed an increase in motion from laminectomy to capsulectomy, then a decrease following facetectomy. A possible explanation for this post-facetectomy behavior was discussed by Panjabi et al. (1975). In the human, this work described the importance of facets to angular rotation during flexion. By sliding upon one another, the facets were able to constrain the horizontal movement and induce the occurrence of rotation of one vertebra upon another. When the facets were disrupted, these properties were eliminated. The result was an increase in horizontal movement and the observed decrease in angular motion following facetectomy.

Although statistical tests of the data from figure 2 only revealed significance for C4-5 in figure 2A, the observed trends appeared to be consistent throughout. Perhaps increased sample size from the 5 spines used in this investigation could have produced more noticeable statistical differences in range of motion.

Comparison of the Canine to the Human

A. Intact Cervical Spine

In the first part of this discussion, which concerned the intact canine cervical spine, two key observations were made. First, there seemed to be a characteristic distribution of motion with respect to vertebral level, depending on the type of motion involved. Second, the relative magnitudes of motion, when comparing the different types, showed that the greatest values existed for lateral bending, less for flexion-extension, and the least for axial rotation. Figures 3A, 3B, and 3C combine the data for the intact canine with analogous data for the intact human as published by Lysell (1969). The white bars correspond to the canine data and the shaded bars correspond to the human data.

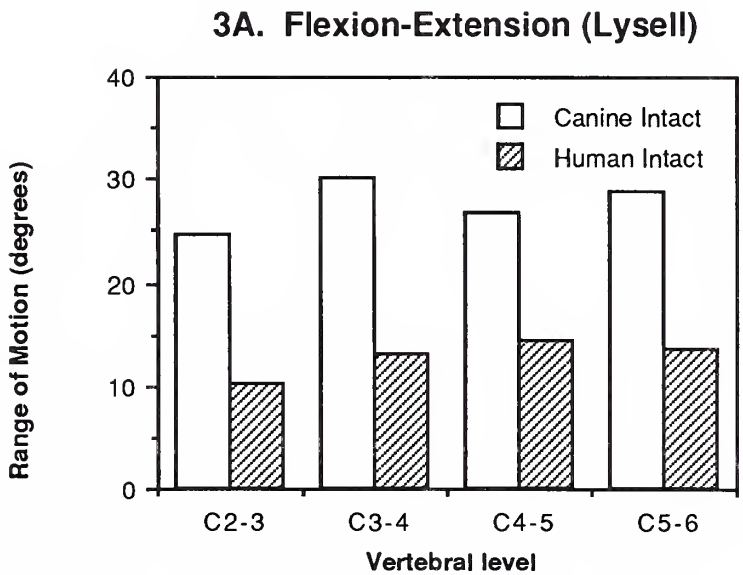


FIGURE 3A. Flexion-Extension of the Intact Canine Versus the Intact Human. The data for the intact canine cervical spine is presented graphically along with analagous data for the intact human. The human data is adapted from Lysell (1969). The horizontal axis corresponds to the vertebral level and the vertical axis represents the range of motion in degrees. Please see the text for a discussion of the graph.

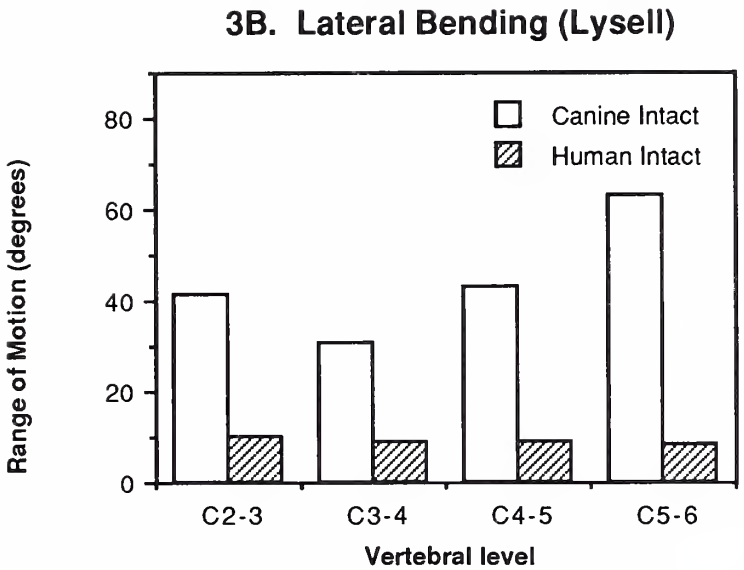


FIGURE 3B. Lateral Bending of the Intact Canine Versus the Intact Human. The data for the intact canine cervical spine is presented graphically along with analogous data for the intact human.. The human data is adapted from Lysell (1969). The range of motion includes the total rotation from both sides. The horizontal and vertical axes correspond to the vertebral level and range of motion, respectively. Please see the text for a discussion of the graph.

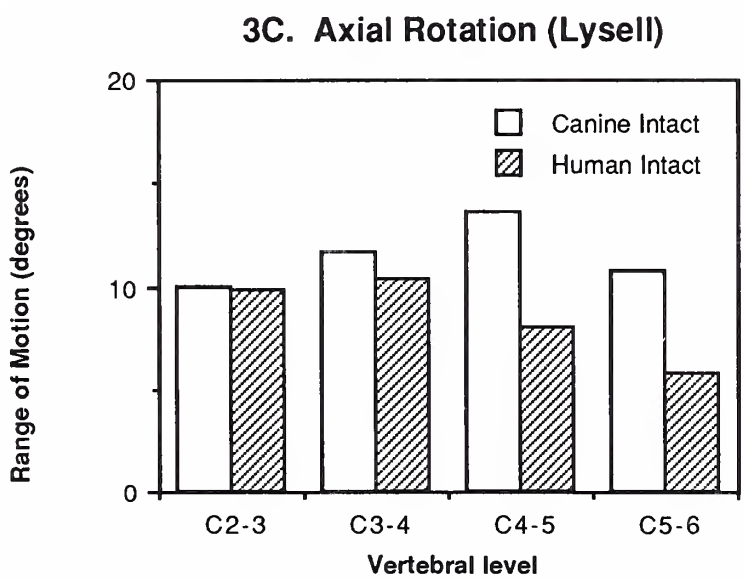


FIGURE 3C. Axial Rotation of the Intact Canine Versus the Intact Human. The data for the intact canine cervical spine is presented along with analagous data for the intact human. The range of motion is the total sum of the clockwise and counterclockwise rotations. The human data is adapted from Lysell (1969). The horizontal and vertical axes are organized as in figures 3A and 3B. Please see the text for a discussion of the graph.

When comparing the characteristic distribution of motion of the intact canine to the intact human with respect to vertebral level , the canine showed a variation from vertebra to vertebra during flexion-extension (figure 3A), while the human appeared to show a pattern of increase toward the middle region (C4-5). Lysell (1969) included this in his discussion as well as the observations that in the intact human cervical spine, lateral bending (figure 3B) varied little, while axial rotation (figure 3C) showed a pattern similar to that of flexion-extension. As seen in figure 3C, the canine behaved in a similar fashion to the human for axial rotation showing the greater motion at the middle levels. However, for lateral bending (figure 2B), it differed. The range of motion showing a tendency to be greater at the two ends (C2-3 and C5-6) as opposed to showing no tendency. In summary, the canine and human intact cervical spines appeared to differ with respect to the relative distribution of motion from vertebra to vertebra in flexion-extension and lateral bending, but were alike in distribution for axial rotation.

When comparing the relative magnitudes of motion with respect to the different types of motion, figures 3A, 3B, and 3C demonstrated that the canine spine was most flexible in lateral bending (30°-60°), followed in order by flexion-extension (20°-30°) and axial rotation (~10°). The human, in contrast, was most flexible in flexion-extension (10°-15°), followed in order by lateral bending (~10°) and axial rotation (5°-10°). In addition, the range of motion values of the canine were much greater overall than those of the human.

These observations would suggest that perhaps the canine relies more heavily upon lateral bending than the human does, perhaps because of its quadrapedal stance. In this stance, lateral bending would seem to allow the canine to survey the horizon more effectively. The human, on the other hand, uses mostly axial rotation to accomplish this task. With regards to the overall increased flexibility of the canine cervical spine over its human counterpart, this could be teleologically related to stance

as well. Because humans stand erect, they possess a superior vantage point for viewing the environment. The increased flexibility of the canine, therefore, could have developed as partial compensation for being a quadraped.

B. Injured Cervical Spine

The second part of this discussion, covering the three-dimensional motion of the injured canine cervical spine, illustrated two important ideas. First, an interaction between the injured vertebra and the uninjured vertebrae seemed to exist such that not only was the injury site affected by its own structural disruption, but also the other vertebrae were affected as well. This behavior was seen in the human cervical spine by Goel et al. (1984). Figures 4A and 4B represent some of the data adapted from that study to facilitate comparisons with the canine.

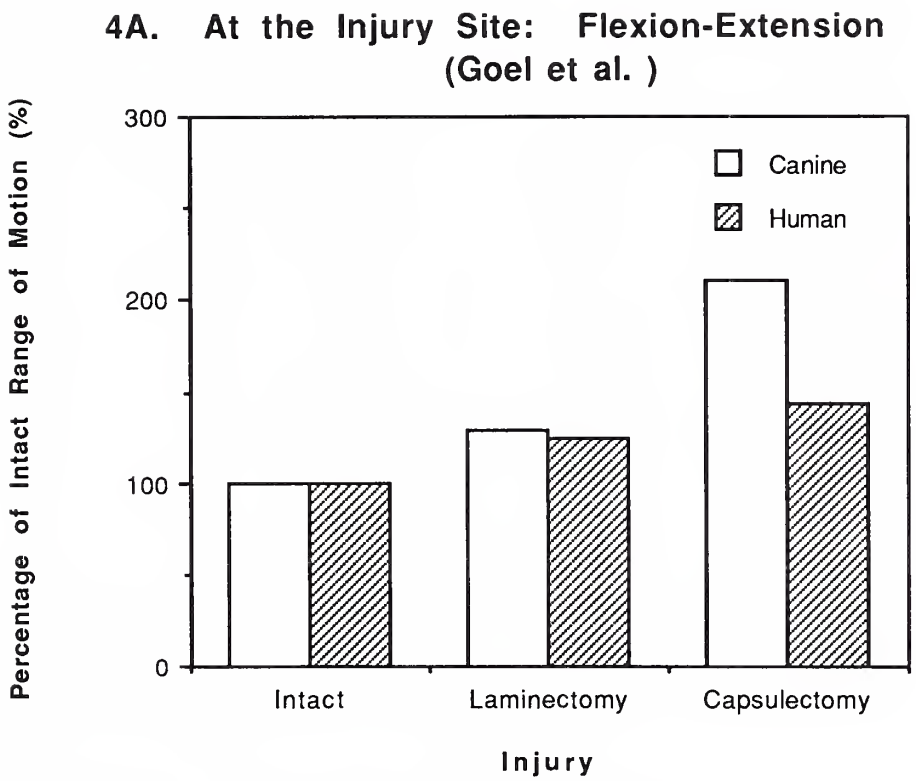


FIGURE 4A. At the Site of Injury: Flexion-Extension of the Injured Canine Versus the Injured Human. For flexion-extension, this graph represents the range of motion for the injured canine along with analogous data for the injured human at the injury site. The human data is adapted from Goel et al. (1984).

The vertical axis represents the percentage of the intact motion. The horizontal axis represents the injury groups. Please see the text for a discussion of the graph.

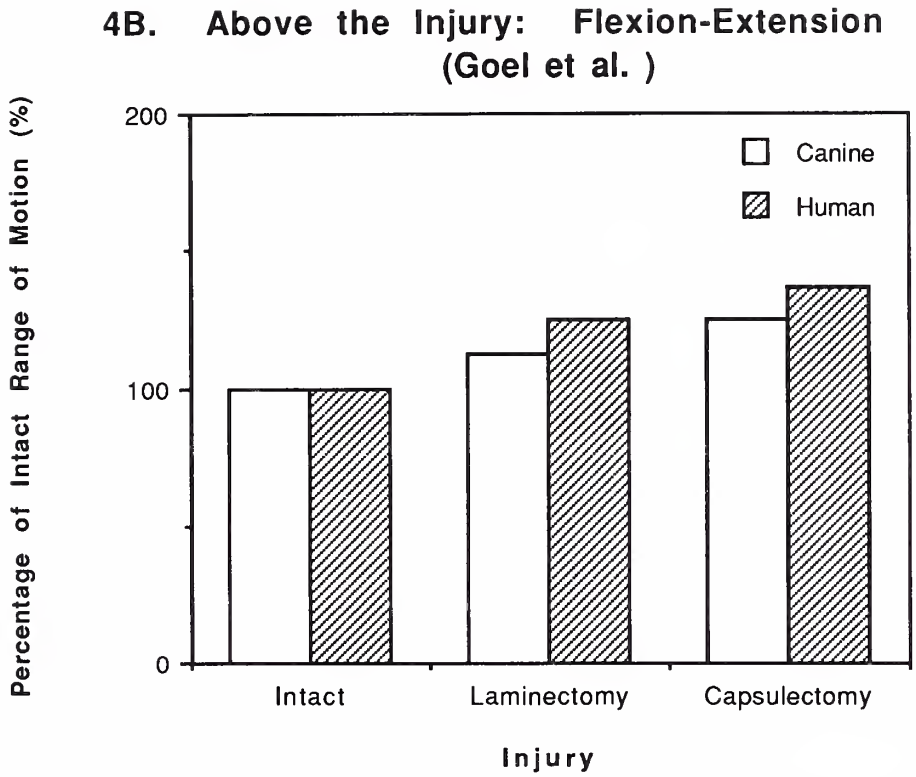


FIGURE 4B. One Level Above the Injury: Flexion-Extension of the Injured Canine Versus the Injured Human. This graph represents data for the injured canine along with analogous data for the injured human one level above the injury site for flexion-extension. The human data is from Goel et al. (1984).

The vertical and horizontal axes correspond to the percentage of the intact motion and the injury groups, respectively. Please see the text for further details

For these figures, the injury groups are located along the horizontal axes. The range of motion as a percentage of that belonging to the intact spine is represented on the vertical axes. Figure 4A compares the flexion-extension of the injured canine to that of the injured human at the site of injury. Figure 4B does the same for the site one level above the injury. Both the canine and the human exhibited an increase in range of motion at the injury site for each sequential injury as seen in Figure 4A. This same behavior applied to the site above the injury as seen in figure 4B.

Figure 4C, representing human data from Panjabi et al. (1975) and White et al. (1975), is set up in a similar manner to figures 4A and 4B. This graph is limited to the

injury site. Also the human data is limited only to flexion because flexion and extension motion were not measured together at the same vertebral level in these studies. Both the canine and the human exhibit the same injury-to-injury pattern described earlier for the canine in part two of this discussion section. This parallel behavior is shown in figure 4C. There was an increase in range of motion at the injury site from laminectomy to capsulectomy, then a subsequent decrease following facetectomy.

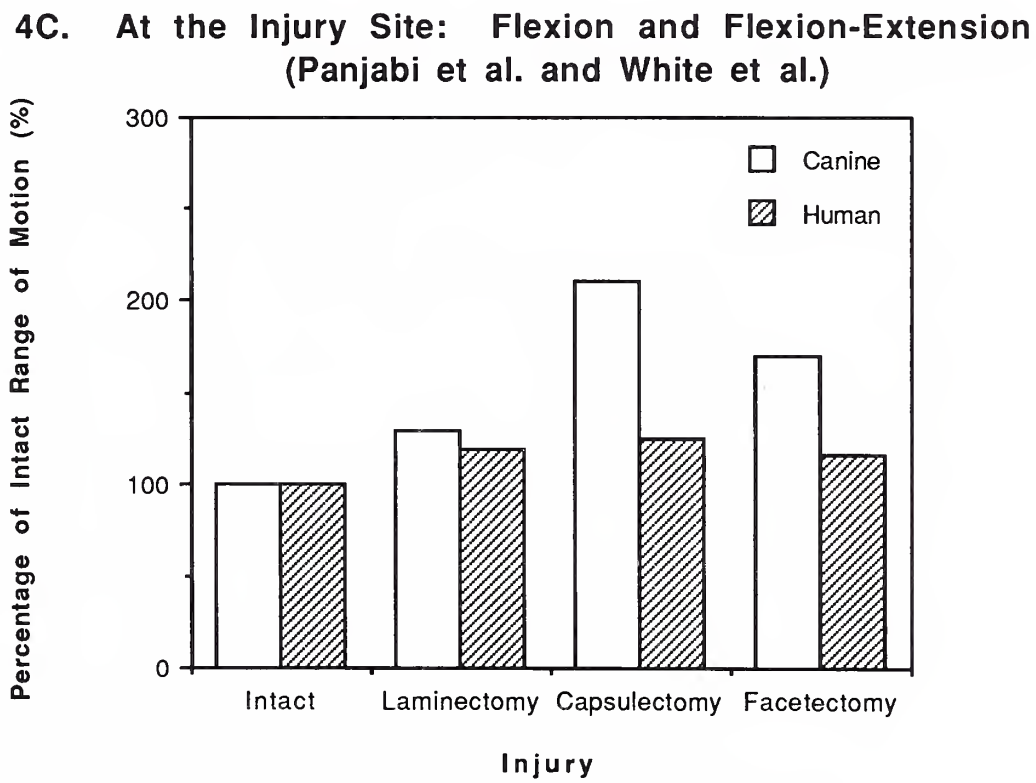


FIGURE 4C. At the Injury Site: Flexion-Extension of the Injured Canine Versus Flexion of the Injured Human. This graph represents the data for the injured canine along with analogous data for the injured human at the site of injury for flexion-extension and flexion, respectively. The human data is from Panjabi et al. (1975) and White et al. (1975). The axes are identical to those of figures 4A and 4B. Please consult the text for a discussion of the graph.

CONCLUSION

In the introduction, the question was raised as to whether or not the canine cervical spine could serve as an accurate model for the human cervical spine, regarding motion and stability. The hypothesis at the time was that the canine, both intact and injured, possessed important similarities to the human. By illustrating the three-dimensional motion of the canine and then comparing this data to previously published human data, the hope was to support the hypothesis.

The main findings of this study included the observation that in the intact cervical spine, the motion of the canine differed from that of the human with respect to how it was distributed among the various vertebral levels for flexion-extension and lateral bending. In axial rotation, however, the distributions were similar. In addition, the intact canine was generally much more flexible than its human counterpart. Also the canine appeared to rely more on lateral bending than the human did.

More interestly, for the injured cervical spine, the canine possessed several similarities to the human. Both spines appeared to behave as cohesive constructs, the vertebrae functioning as interactive elements of the whole unit, as opposed to functioning as independent elements. This idea was illustrated by how injury at one vertebra affected the motion of the other vertebrae. Possibly a combination of loosening and compensation was responsible. The other interesting behavior seen in both the canine and human cervical spines was the pattern at the injury site of an increase in range of motion from laminectomy to capsulectomy, followed by a post-facetectomy decrease.

In conclusion, the canine behaved somewhat differently from the human with regards to motion in the intact cervical spine. However, motion and stability behavior following injury in the canine paralleled those of the human.

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